IS IT POSSIBLE TO IMPROVE OUR KNOWLEDGE OF θ_{13} BY OSCILLATION EXPERIMENTS AT REACTORS ?

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ABSTRACT

The possibility to further constrain the electron neutrino mixing in the atmospheric neutrino domain by nuclear reactor experiments is reviewed. It is shown that the Chooz sensitivity could be improved up to a factor 5 ($U_{e3}^2 = 5 \cdot 10^{-3}$) only in a two-distance experiment carried out at a one-reactor plant and utilizing twin detectors, which is needed to reduce both statistical and systematic uncertainties to 0.5%.

1. Physics motivations

The atmospheric neutrino anomaly, recently confirmed by Super-Kamiokande[1], could be accounted for in terms of $\nu_\mu \leftrightarrow \nu_\tau$ oscillation with $1 \cdot 10^{-3} \leq \delta m_{23}^2 \leq 4 \cdot 10^{-3} \, \mathrm{eV}^2$ in a satisfactory way. Nevertheless, the mixing of electron neutrino in the same domain is not completely ruled and could still be present at a sub-dominant level. In a three-flavour mixing scheme, current limits turn out to be

$$U_{e3}^2 \leq 2.5 \cdot 10^{-2} \text{ at } \delta m_{13}^2 = 3 \cdot 10^{-3} \, \mathrm{eV}^2 \tag{1}$$

mainly due to the null result obtained by the Chooz experiment[2] and, at a minor extent, to Super-Kamiokande itself. The Chooz limit will be improved (up to $U_{e3}^2 \approx 10^{-3}$) by long baseline searches at neutrino factories[3], whose set-up is not beyond the corner (maybe 2010). Therefore an experiment aiming at improving the sensitivity to ν_e-mixing at an intermediate stage between long-baseline reactor and accelerator searches is advisable.

The sensitivity of such an experiment could also extend towards the range of solar neutrinos. As we heard at this Conference, indications in favour of the Large Mixing Angle MSW solution to the solar neutrino deficit come from the analysis[4] of the charged current reaction rate and the recoil electron energy spectrum measured by SNO[5], combined with the Super-Kamiokande data[6]. If so, the KamLAND reactor experiment will say a ultimate word on this puzzle; if confirmed, any other scenario invoking modifications of the Standard Solar Model will be definitely excluded. However, as it was pointed out at this Conference[7], the $\overline{\nu}_e$ survival probability in KamLAND is no longer energy dependent for $\delta m_{12}^2 > 2 \cdot 10^{-4} \, \mathrm{eV}^2$ values (which are still included in the 95% Confidence Interval corresponding to the LMA solution). So

a reactor experiment with intermediate sensitivity could be necessary to probe the upper δm_{12}^2 part of this interval.

1.1. The goal

The Chooz result is compatible with the absence of $\overline{\nu}_e$ oscillations in the atmospheric neutrino range, as the ratio of measured vs. expected flux turns out to be

$$R = 1.01 \pm 2.8\% \text{ (stat)} \pm 2.7\% \text{ (syst)} \qquad (2)$$

This result has been recently confirmed by the Palo Verde collaboration, which obtained[8]

$$R = 1.01 \pm 2.4\% \text{ (stat)} \pm 5.3\% \text{ (syst)} \qquad (3)$$

As the sensitivity to the mixing parameter is roughly linear with the overall uncertainty, both statistical and systematic error must be lowered to $\approx 0.5\%$ in order to push the current limit down by a factor 5.

The bulk of the systematics (about 2%) is due to the knowledge of the $\overline{\nu}_e$-flux from the reactors (in the case of Palo Verde a larger contribution is inherent in the background subtraction method[9]). This uncertainty is ruled out by comparing the neutrino fluxes and spectra at two distances, namely $L_1 \approx 100$ m and $L_2 \approx 1000$ m; this makes the test independent of absolute normalisation (which includes neutrino spectra, cross-sections, reactor power and burn-up). The two detectors need to be identical (or as similar as possible) so as to minimise the residual contribution due to the detector parameters (detection efficiencies, energy calibration).

Concerning the statistics, an improvement could be obtained by using larger detectors (10 times more than Chooz for the far detector) so as increase the neutrino sample. As we shall see later, the statistical accuracy strongly relies on the background subtraction. An efficient suppression of muon-induced neutron background (which was the major noise source in Chooz) requires underground detectors, at a depth ≈ 300 m.w.e. The accidental background must also be kept under control by shielding the neutrino target from external radioactivity. Let us see a possible experimental layout.

2. A possible experiment

2.1. The detector

The $\overline{\nu}_e$ detection is based on the usual inverse β-decay reaction

$$\overline{\nu}_e + p \rightarrow n + e^+ \qquad (4)$$

and makes use of the $e^+ - n$ delayed coincidence technique. While past long-baseline experiments made use of Gd-doped liquid scintillator as a $\overline{\nu}_e$ target, a standard liquid scintillator (*i.e.* not Gd-loaded) is planned for this experiment. This choice is somewhat based on our experience with former type of scintillators, whose stability cannot be guaranteed to be better than 0.5% all over the data taking period (~ 1000 d).

Two drawbacks immediately follow. First, the neutron signal, associated with 2.2 MeV γ-emission, is not separated in energy from radioactivity (as in the case of the 8 MeV γ-line due to capture on Gd). Second, the capture delay ($\tau \sim 170\,\mu$s) is 5 times as long as in Chooz; the time window to search for the $e^+ - n$ coincidence must be scaled accordingly, if we wish to preserve the neutron efficiency. As a consequence of this, the accidental background is potentially more dangerous than in Chooz and needs to be kept under control by adopting a detector design suited to shield the neutrino target against external radioactivity. Therefore a mini-version of KamLAND[10] or Borexino detectors is taken into account.

A possible layout could be that shown in Fig.1, according to an idea by Mikaelyan[11] (see next section). It consists of three concentric regions, from the inner to the outer side:

1) the neutrino target, containing 50 T of liquid scintillator (mineral oil + PPO);

2) a 1 m thick mineral oil buffer, providing proper optical coupling with the PMTs and a shield against PMT radioactivity at the same time;

3) an active veto to tag cosmic muons crossing the detector as well as to shield the inner volume against external detector activity.

1000 inward-looking PMTs are located outside region 2, thus providing $\sim 20\%$ photo-cathodic coverage and a photoelectron yield ~ 150 pe/MeV.

Material radio-purity should not be a concern for this type of experiment. With U and Th content at levels of 10^{-13} g/g (not a severe requirement), the accidental background rate could be easily kept at less than a few events a day just by applying standard correlation (both in space and time) cuts.

2.2. The Kr2Det project

An experiment was proposed to be worked out at the underground nuclear plant located in Krasnoyarsk, Siberia. Here one of the three old reactors (originally devoted to Plutonium production for nuclear weapons) is still under operation with a thermal power production of $W = 1.6$ GWth to supply the inhabitants of nearest cities with electricity and heat. This site would offer unique features:

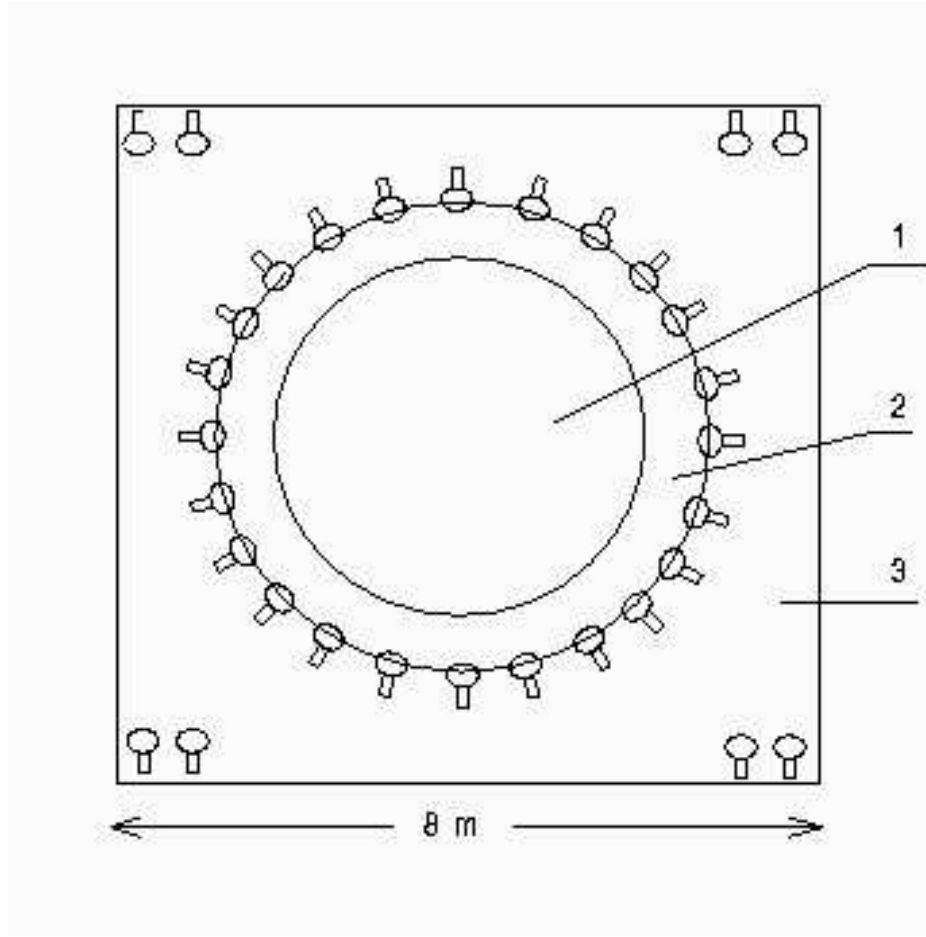a) two underground sites located at distances $L_1 = 250$ m and $L_2 = 1100$ m;

Figure 1: Schematic view of the detector proposed for the Kr2Det experiment; the three concentric regions explained in the text are indicated.

b) a thick ($\approx$ 600 m.w.e.) rock overburden, implying a neutron flux reduction by a factor $\sim$ 3 with respect to Chooz;

c) the possibility to measure the background during the reactor stop for refueling.

The $\overline{\nu}_e$-flux is measured simultaneously by two twin detectors of the type shown in Fig:1 and with the characteristic already listed in the previous section. The use of identical detectors, combined with the possibility to swap their position, makes a systematic error $\sigma_{syst} \sim 0.5\%$ within the reach of the experiment.

The expected signal rate is $\sim 50\,\mathrm{d}^{-1}$ for the far detector and $\sim 1000\,\mathrm{d}^{-1}$ for the near one. About 3 years running are thus necessary to cumulate 40000 $\overline{\nu}_e$ events, so as to obtain a statistical error $\sigma_{stat} \sim 0.5\%$. The overall background rate is expected to be $5\,\mathrm{d}^{-1}$.

Unfortunately this experimental program is far from being safe, as Russian authorities are strongly pressed to stop reactor operations for safety reasons. So we are

forced to consider possible alternatives to Kr2Det.

2.3. An alternative experimental frame

Let us consider an experiment to be carried out at Chooz (let us name it "Chooz2"). The old Chooz detector site, located at an average distance of ~ 1000 m from the two reactors, could be used to host the far detector. The near detector instead should be placed in a new shallow site ($L_1 \sim 100$ m, 40 m.w.e. depth) to be excavated on purpose, in order to suppress the hadronic components of cosmic rays. The muon vertical intensity instead would be reduced to only 30% of the surface intensity. Two main difficulties immediately arise:

1) with such a huge muon flux, it is impossible to maintain the size of the near detector (else it would be blind for most of the time). A 5 T scintillator target looks like a more reliable compromise between signal collection and background suppression; the neutron background is expected to be $\sim 30\,\mathrm{d}^{-1}$. On the other hand, the far detector needs to be as large as above in order to reduce the statistical error at the quoted level;

2) it is quite unlikely that both reactors simultaneously stop (apart from troubles) for refueling, so that it is impossible to completely turn off the signal source (this favourable circumstance was in fact available only to the Chooz experiment).

The first point affects the systematics. It must be recalled that our previous estimate strongly relies on the use of identical detectors (both in size, shape and rock overburden), with the further possibility to swap their position. In an an experimental frame with two differently sized detector, one has to face with differences in both detection efficiency and calibration. Based on our experience, we expect that the systematic uncertainty could not be better than 1%.

The second point limits the statistical accuracy. With at least one reactor always ON, experiments can rely on the power variations which occur during refueling of one reactor in order to subtract the background. In this case only a small fraction of the neutrino events are used as signal while most of them are subtracted away with the background; the smaller the power excursion, the larger the statistical error. Since reactors are usually operated at their full power (for obvious economical reasons) for most of the time, the statistical error is dominated by the short refueling periods; the majority of the data taken by such an experiment is not useful to improve the accuracy. Let us evaluate the expected sensitivity by considering a realistic plant operation scenario.

2.4. Signal and background

Let us consider a two-reactor plant (as in the case of Chooz2) with both reactors

normally operating at full power. Let us assume reactor cycles with 10 months dura-
tion (9 months operation + 1 month stop for refueling). So, during three years data
taking one collects:

a) $\sim 800\,\mathrm{d}$ with both reactors ON ("ON" period);

b) $\sim 200\,\mathrm{d}$ with one reactor OFF ("OFF" period).

During the ON period, the expected signal rate for the far detector is $\sim 125\,\mathrm{d}^{-1}$,
about 5 times as high as in Chooz, as a result of an improved target volume (by
10) and a reduced (by one half about) neutron efficiency. The neutron background
(which was $\sim 1\,\mathrm{d}^{-1}$ in Chooz) should scale accordingly. We then expect an overall
signal of $\sim 10^5$ events, corresponding to a rate of

$$R_2^{ON} = (130 \pm 0.4)\,\mathrm{d}^{-1} \tag{5}$$

During the OFF period, the signal rate is roughly halved, while the background is
unaffected. Then ~ 13500 events are collected in 200 d live time, 1000 of which is
background; the OFF rate is then

$$R_2^{OFF} = (67 \pm 0.6)\,\mathrm{d}^{-1} \tag{6}$$

By subtracting (6) from (5) one finally obtains the net signal from one reactor

$$R_2 = (63 \pm 0.7)\,\mathrm{d}^{-1}, \tag{7}$$

with $\sigma_{\mathrm{stat}} = 1.1\%$. It is easy to check that this accuracy does not depend on the
background rate itself, as long as it remains much smaller than the signal. The main
limitations to the statistical accuracy are inherent in the background subtraction
method for the far detector. The near detector does not contribute significantly
(0.3%) to this uncertainty.

2.5. A more optimistic scenario

The background measurement could be improved if, by chance, reactor power
ramps up and down smoothly or, even better, if they are both turned OFF for a
while (both conditions were fulfilled at Chooz). For instance, let us imagine a sudden
plant shut-down lasting 30 d. In this case the background rate for the far detector
could be measured with better than 10% accuracy ($R_2^{OFF} = (5 \pm 0.4)\,\mathrm{d}^{-1}$) and,
moreover, the net signal from the two reactors would be

$$R_2 = (125 \pm 0.6)\,\mathrm{d}^{-1}, \tag{8}$$

implying $\sigma_{\mathrm{stat}} = 0.5\%$, which is our goal.

Just to give a sketch on how far this scenario is from reality, let us evaluate the cost (only in terms of electrical power cut) of such a long shut-down at Chooz2. With 8.5 GWth total thermal power, $\sim 30\%$ conversion efficiency and ~ 0.05 \$/kWh as an average European price, the loss amounts to about 3 M\$ a day, *i.e.* 100 M\$ in one month!

3. Expected sensitivity

We can infer limits to oscillation parameters in the different frames considered so far. Two different kinds of test can be performed:

a) "rate" test, based on the comparison of the integral neutrino rates at two distances;

a) "shape" test, based on the comparison of the neutrino energy spectra.

Let us examine both.

3.1. The rate test

In this case the test variable is

$$r = \frac{R_2}{R_1} \frac{V_1 \varepsilon_1 L_2^2}{V_2 \varepsilon_2 L_1^2},\tag{9}$$

which is the ratio of integral neutrino rates normalised to be 1 in the absence of oscillations (here V, ε indicate the detector volume and the overall detection efficiency). In Eq.(9) the first term contributes the statistics, while the second one is related to the systematics. We use a statistic test based on $\Delta\chi^2$ instead of the likelihood ratio (which is a good approximation in a Gaussian regime); the χ^2 is given by

$$\chi^2 = \left(\frac{r_{\mathrm{meas}} - r_{\mathrm{exp}}(\delta m^2, \theta)}{\sigma} \right)^2,\tag{10}$$

where $r_{\mathrm{meas}}, r_{\mathrm{exp}}$ are the measured and the expected ratio (the latter depending on the oscillation parameters) and σ results from adding the statistical and the systematic error in quadrature. Then the Feldman-Cousins prescription[12] is applied to obtain the sensitivity contour at 90% C.L. for both Kr2Det and Chooz2; the contour plots obtained are shown in Fig.2. The limits to the mixing angle at a given δm^2 depend linearly on the overall uncertainty. At $\delta m^2 = 3 \cdot 10^{-3}\,\mathrm{eV}^2$ (which is the best value of Super-Kamiokande fit to atmospheric neutrino data), the Chooz2 sensitivity is $\sin^2(2\theta) = 0.04$ (or equivalently $U_{e3}^2 = 10^{-2}$). The Kr2Det sensitivity, computed by assuming 0.5% accuracy (for either statistics and systematics) is twice better than Chooz2 and improves the Chooz limit by a factor 5, which is our goal. The sensitivity to mass values turns on at $3 \cdot 10^{-4}\,\mathrm{eV}^2$ in the case of Kr2Det, which could provide
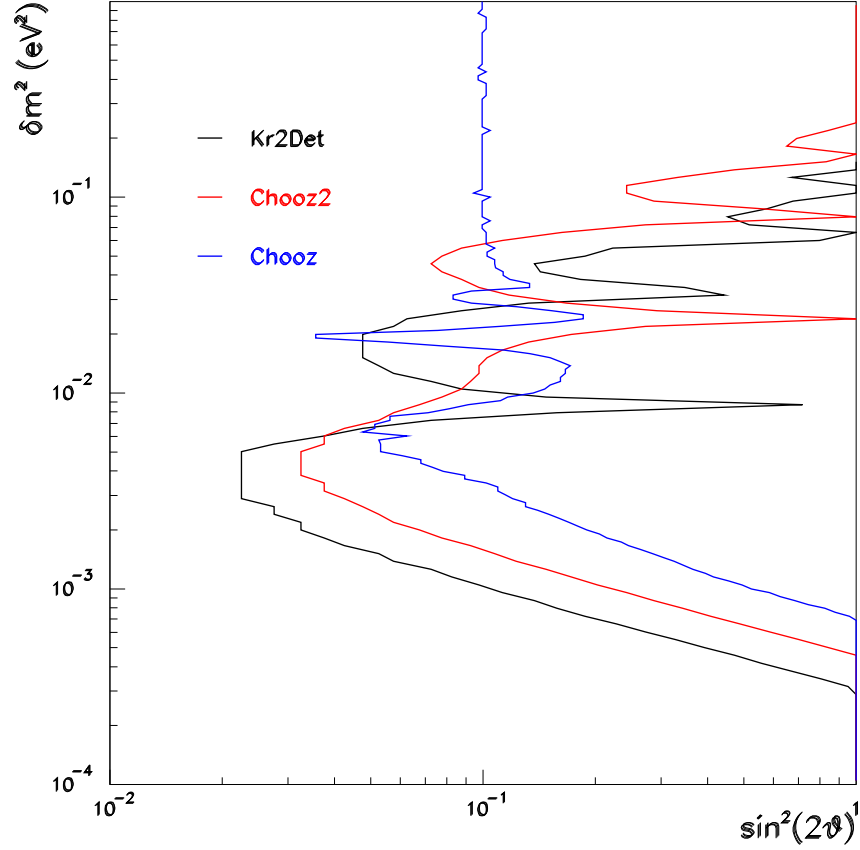
Figure 2: Sensitivity plot at 90% C.L. obtained for the rate test in the case of Kr2Det and Chooz2. The Chooz contour is also shown for comparison.

a significant overlap with the KamLAND domain; the limit is poorer in the Chooz2 case ($5 \cdot 10^{-4} \, \text{eV}^2$).

3.2. The spectrum test

The sensitivity could be slightly improved by using the comparison of positron energy spectra at the two distances. Since the positron energy is strongly correlated with the incoming $\overline{\nu}_e$, modulations in the ratio of the two spectra could provide an evidence for the dependence of the $\overline{\nu}_e$ survival probability on the energy, which is typical of oscillations. Spectra are arranged in $n = 16$ bins from 0.8 to 7.2 MeV. So we build the statistic as

$$\chi^2 = \sum_{i=1}^{n} \left(\frac{r_{\text{meas}}(E_i) - \alpha r_{\text{exp}}(gE_i, \delta m^2, \theta)}{\sigma_{\text{stat}}(E_i)} \right)^2 + \left(\frac{\alpha - 1}{\sigma_\alpha} \right)^2 + \left(\frac{g - 1}{\sigma_g} \right)^2, \qquad (11)$$

where E_i is the i-th bin e$^+$ visible energy [a] and α, g are systematic parameters respectively concerning the spectra normalisation (relative efficiencies, target volumes) and the energy scale calibration. The χ^2 value for a certain parameter set $(sin^2(2\theta), \delta m^2)$ is determined by minimising (11) with respect to the gain factor g and the normalisation α. We adopted again the Feldman-Cousins "ordering" principle to determine the sensitivity domains at 90% C.L. as a function of the experimental accuracies. The contours obtained with 0.5% statistical accuracy (which is the case of Kr2Det or Chooz2 with a one-month shut-down) are shown in Fig.3. The normalisation error could vary depending on the experimental frame considered; we could have $\sigma_\alpha = 0.5\%$ in the case of identical detectors (such as in Kr2Det), else it is unlikely to have better 1%. The sensitivity to the mixing angle at $\delta m^2 = 3 \cdot 10^{-3} \, \mathrm{eV}^2$ is $sin^2(2\theta) = 0.015$ for the former and 0.025 in the latter case. It is also interesting to note that the sensitivity does not turn off (as in the case of the rate test) if there is no constraint at all on the relative normalisation ($\sigma_\alpha = \infty$). The mass sensitivity turns on at $2.5 \cdot 10^{-3} \, \mathrm{eV}^2$ in the most favourable case, else at $3.5 \cdot 10^{-3} \, \mathrm{eV}^2$.

The sensitivity is poorer in the more realistic frame of alternating reactor stops, as shown in Fig.4. With 1.1% statistical accuracy, the mixing angle limit is $sin^2(2\theta) = 0.03$ if $\sigma_\alpha = 0.5\%$; in the case of 1% systematic uncertainty, this limit increases up to $sin^2(2\theta) = 0.04$, only twice better than Chooz.

4. Conclusions

The $\nu_e \leftrightarrow \nu_x$ mixing could be present at a subdominant level in the atmospheric neutrino range and will be investigated at future neutrino factories down to $U_{e3}^2 = 10^{-3}$. A reactor-based experiment could push the current limit set by Chooz to an intermediate step ($U_{e3}^2 = 5 \cdot 10^{-3}$) if:

- both detectors were underground located, so as to keep the systematic accuracy under 0.5%;

- the background would be measured with reactors OFF (one-reactor plants are preferred), so that $\sigma_{syst} = 0.5\%$.

If one of this conditions is not fulfilled, it is difficult to gain more than a factor $2 \div 3$ in mixing angle sensitivity with respect to Chooz.

5. Acknowledgements

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[a]In single vessel detectors the bulk signal is the positron kinetic energy boosted by 1 MeV energy loss of the two γ's. from annihilation.
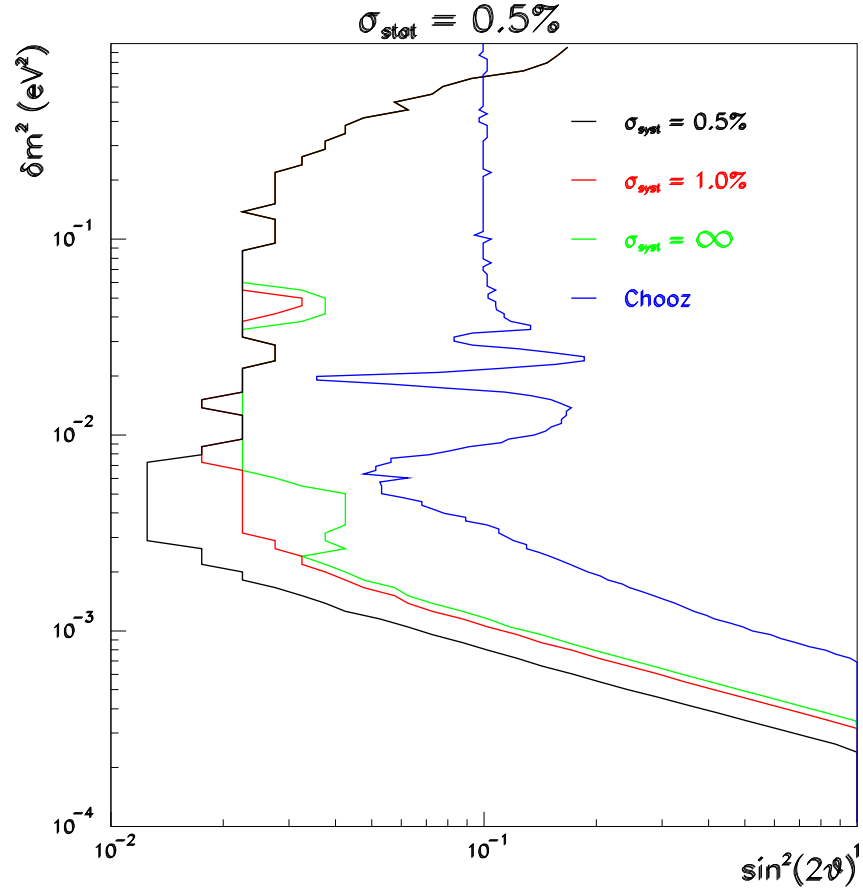
Figure 3: 90% C.L. plot obtained by the spectrum test with 0.5% statistical accuracy for different values of the normalisation error.

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6. References

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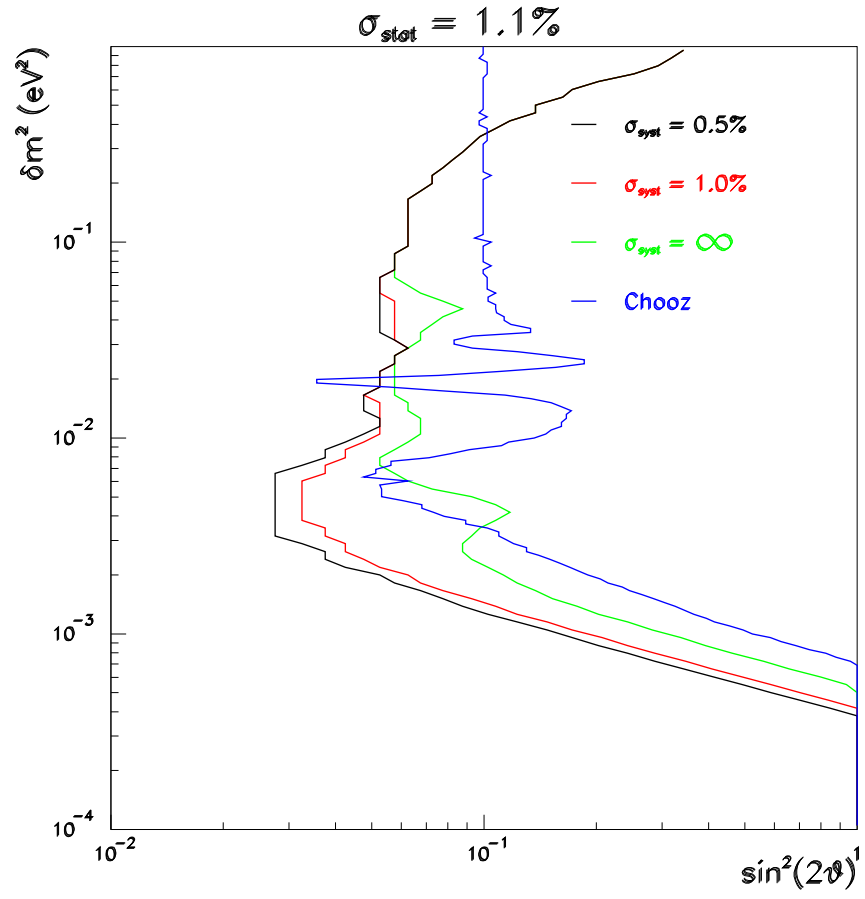9) Y. F. Wang, L. Miller and G. Gratta, *Phys. Rev.* **D62** (2000) 013012.

Figure 4: The same as before, with 1.1% statistical accuracy.

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